HIGH EFFICIENCY CLEAN COMBUSTION IN MULTI-CYLINDER LIGHT-DUTY ENGINES

Scott Curran (PI), Adam Dempsey, Zhiming Gao, Vitaly Prikhodko, Jim Parks, David Smith and Robert Wagner

Fuels, Engines and Emissions Research Center
Oak Ridge National Laboratory

Gurpreet Singh, Ken Howden, Leo Breton
Vehicle Technologies Office
U.S. Department of Energy

2015 DOE Hydrogen Program and
Vehicle Technologies Annual Merit Review

June 10, 2015

ACE016

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High Efficiency Clean Combustion Project Overview

Activity evolves to address DOE challenges and is currently focused on milestones associated with Vehicle Technologies efficiency and emissions objectives.

Timeline

- Consistent with VT MYPP
- Activity scope changes to address DOE & industry *needs*

Barriers (MYPP 2.3 a,b,f)*

a) Lack of fundamental knowledge of advanced combustion regimes

b) Lack of effective engine controls for LTC

f) Lack of emissions data on future engines

Budget

FY 2013 – $600k

FY 2014 – $500k

FY 2015 – $430k

Partners / Interactions

Regular status reports to DOE

Industry technical teams, DOE working groups, and one-on-one interactions

Industry: GM, MAHLE, Honeywell, and many others

Universities: U. Wisconsin, U. Minnesota, Clemson

Consortia: CLEERS, DERC

VTO & DOE Labs: VSS, FLT, LANL, PNNL, SNL, ANL

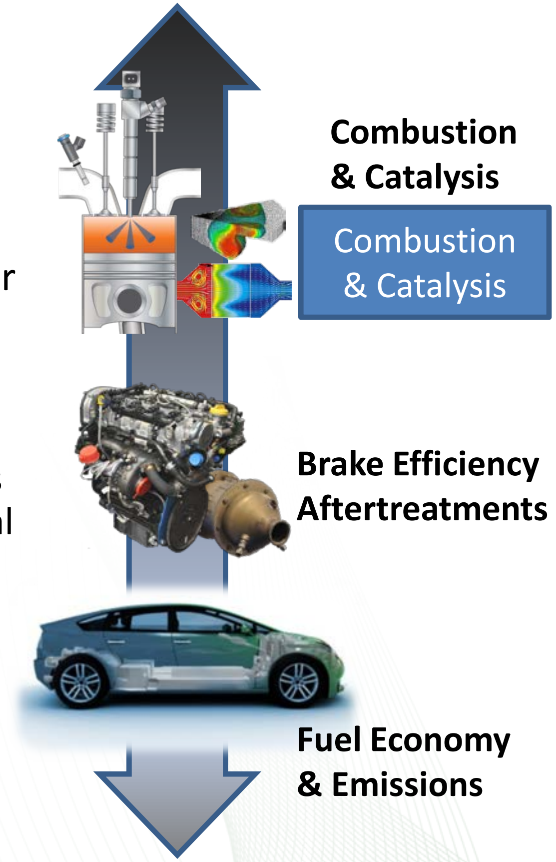
ORNL: fuels, emissions, vehicle systems, others

*http://www1.eere.energy.gov/vehiclesandfuels/pdfs/program/vt_mypp_2011-2015.pdf

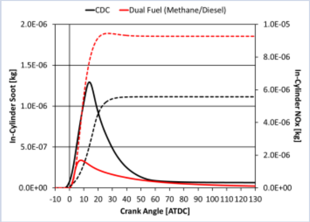
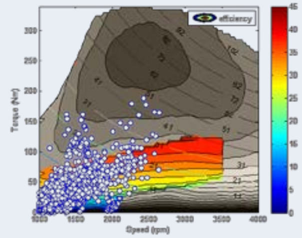
Relevance and Project Objectives

- **Overall Objective Focused on DOE VTO Milestones**
  - **Addressing barriers to meeting VTO goals of reducing petroleum energy use (engine system) including potential market penetration with efficient, cost-effective aftertreatments.**

- **Relevance to VTO Program Objectives (MYPP 2.3-3)**
  - **To develop and assess the potential of advanced combustion concepts, such as RCCI, on multi-cylinder engines for improved efficiency and emissions along with advanced emission control technologies (aftertreatments).** (Backup slide on RCCI)
  - **Investigating high efficiency concepts** developed on single-cylinder engines and addressing multi-cylinder engine/ aftertreatment implementation challenges.
    - **Characterize emissions** from advanced combustion modes and define the synergies and any incompatibilities with aftertreatments with the expectation that engines may operate in both conventional and advanced combustion modes including **multi-mode.**
    - **Minimize aftertreatments** and minimize fuel penalties for regeneration *(Tier III goal).*
  - **Interact in industry/DOE tech teams** and CLEERS to respond to industry needs and support model development.



FY 15 Milestones Met or On Track

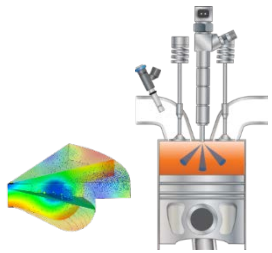
Month/ Year	Milestone	Description	Status	
Dec/ 2014	Milestone	Demonstrate modeling capability of RCCI combustion[1]	**COMPLETE**	
June/ 2015	Milestone	Develop experimental RCCI map suitable for drive cycle simulations	ON SCHEDULE	
Sept/ 2015	Smart Milestone	Demonstrate 30% increase in modeled fuel economy with RCCI over LD drive cycles [2] (JOULE)	ON SCHEDULE	

[1] *In collaboration with Convergent Science*

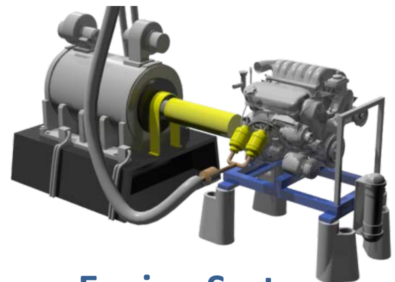
[2] *In collaboration with VSST support task*
VSS 140 Impacts of Advanced Combustion Engines

Approach: Multi-Cylinder Advanced Combustion with Production-Grade Hardware and Aftertreatment Integration

- **Systems level investigation into high efficiency combustion concepts on MCEs**
  - Combine multi-cylinder advanced combustion and emissions control research to identify barriers to LTC implementation and provide model feedback.
  - Work with industry, academia and tech-teams to clearly define benefits and challenges associated with "real-world" implementation of advanced combustion modes including efficiency, controls and emissions.



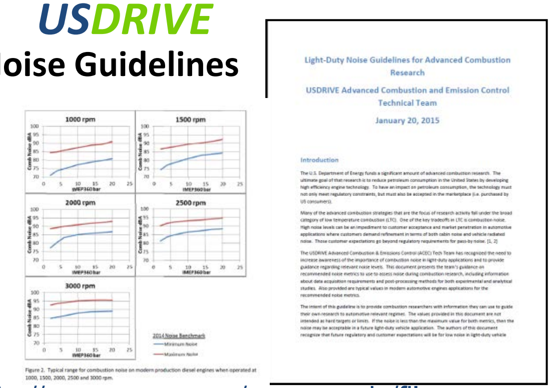
Combustion
Metric: Indicated efficiency



Engine System
Metric: Brake efficiency

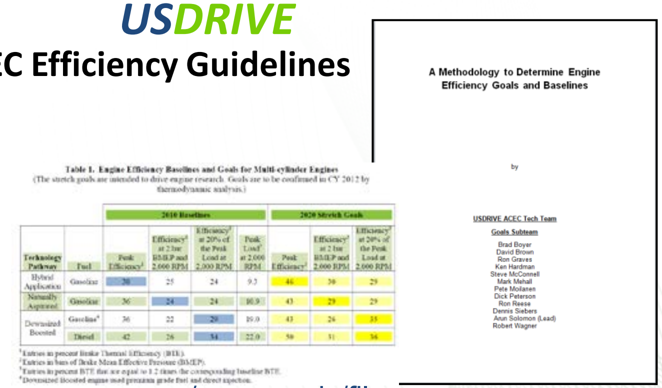
Full Vehicle
Metric: Fuel Economy

USDRIVE
ACEC Noise Guidelines



http://www.uscar.org/commands/files_download.php?files_id=399

USDRIVE
ACEC Efficiency Guidelines



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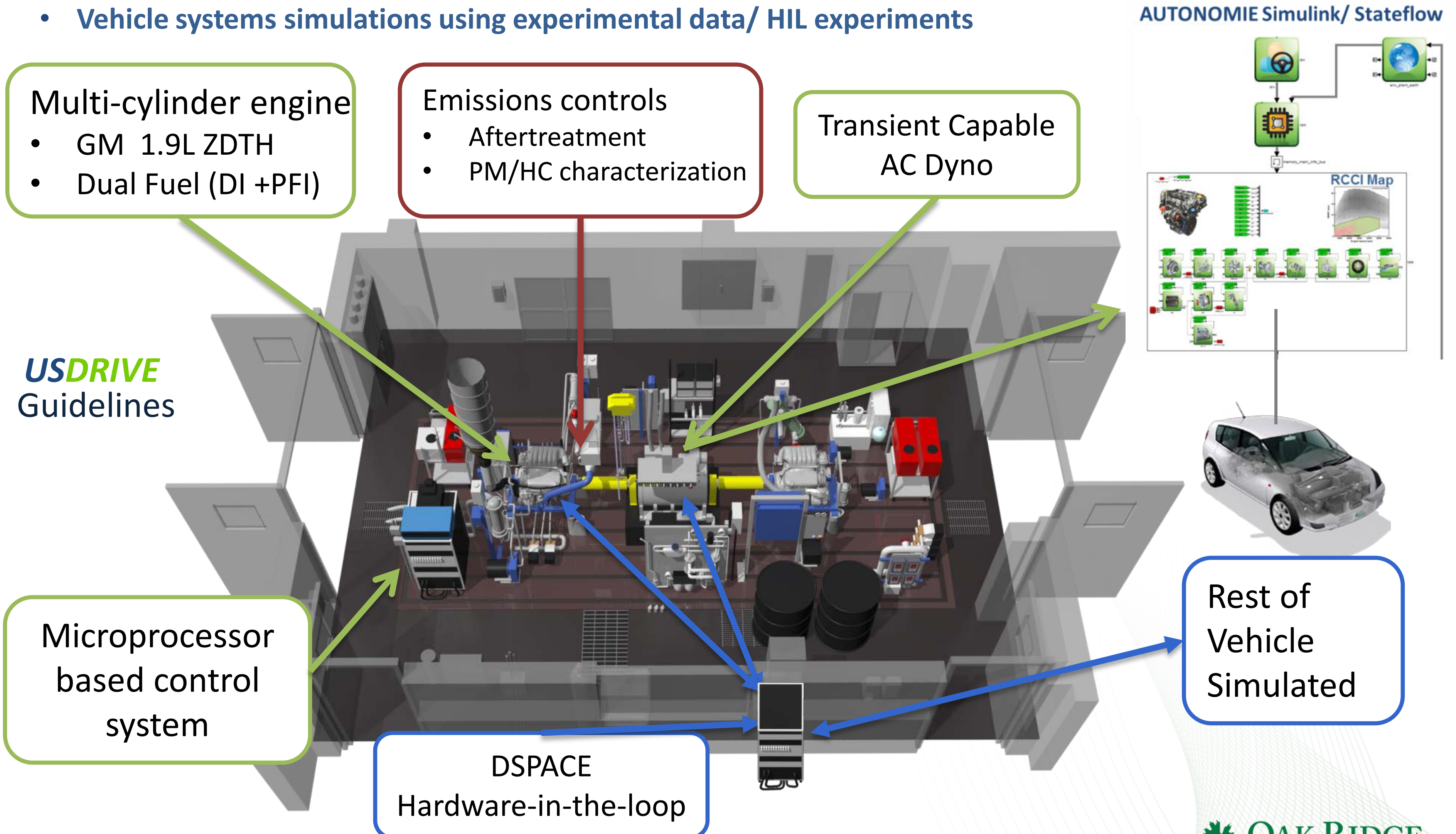
Approach: Multi-cylinder investigations of LTC including aftertreatments leading to vehicle systems simulations

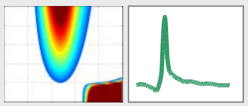
- GM 1.9L ZDTH Diesel Engine with dual-fuel system
- Emissions characterization and aftertreatment evaluation
- Vehicle systems simulations using experimental data/ HIL experiments



ORNL 2014 DOE Milestones – Advanced Combustion Engines

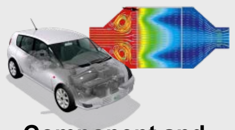
Accomplishments (1/9)

- **Q3 Milestone – High Efficiency RCCI Mapping**
  - Developed RCCI combustion map on a multi-cylinder engine suitable for light-duty drive cycle simulations

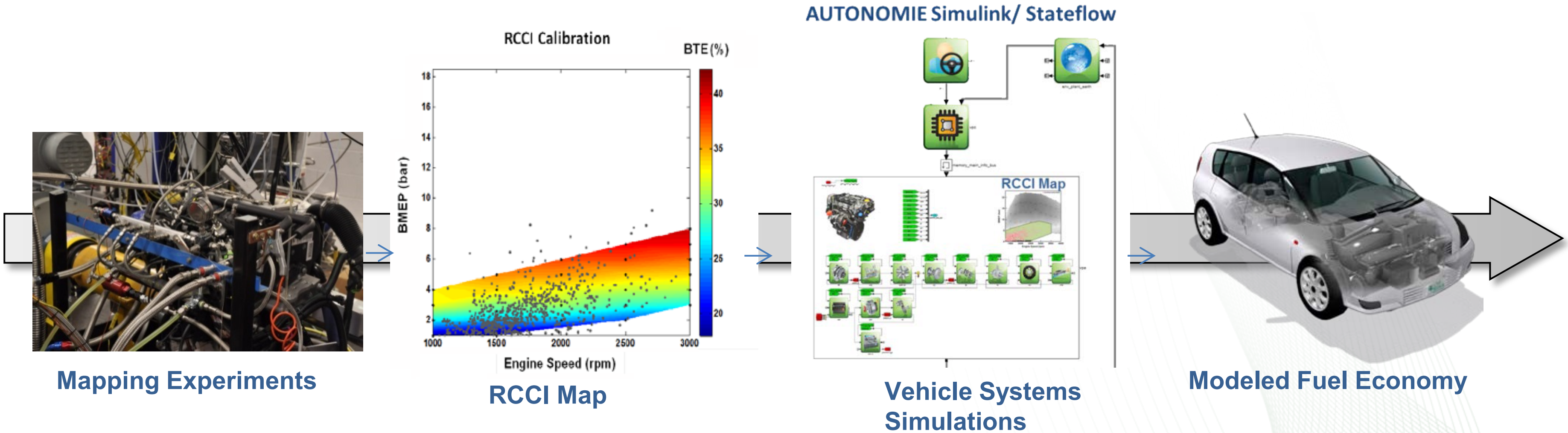


Advanced (HECC) Combustion

- **Q4 Milestone – RCCI Vehicle Systems Modeling**
  - Demonstrate modeled fuel economy improvement of **25%** for passenger vehicles solely from improvements in powertrain efficiency relative to a 2009 PFI gasoline baseline
    - Perform drive cycle simulations on same vehicle platform to estimate fuel economy and engine out emissions



Component and System Modeling



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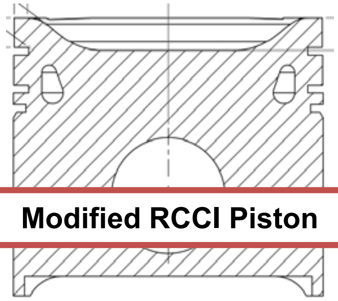
Q3 Milestone RCCI Mapping with Gasoline and Diesel

- **Mapping was carried out using systematic procedure for achieving highest efficiency with lowest possible emissions without direct use of modeling. (Modified Pistons)**
  - Curran,.,et al., IJER, 2012.
- **Self imposed constraints of 10 bar/deg MPRR (upper) and CO limit of 5000 ppm (lower) (pre-ACEC noise guidelines)**
  - Mapping limits and guidelines being developed in collaboration with ANL (ACE011)
- **Single DI pulse at the lower engine loads and lower speeds, and a split pulse at higher engine loads.**



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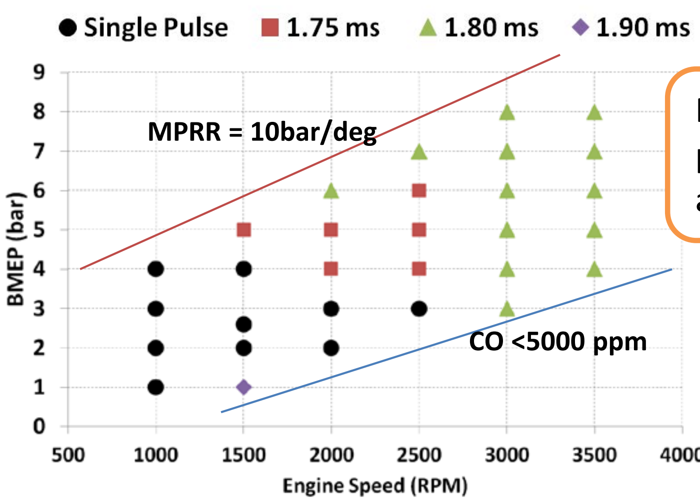
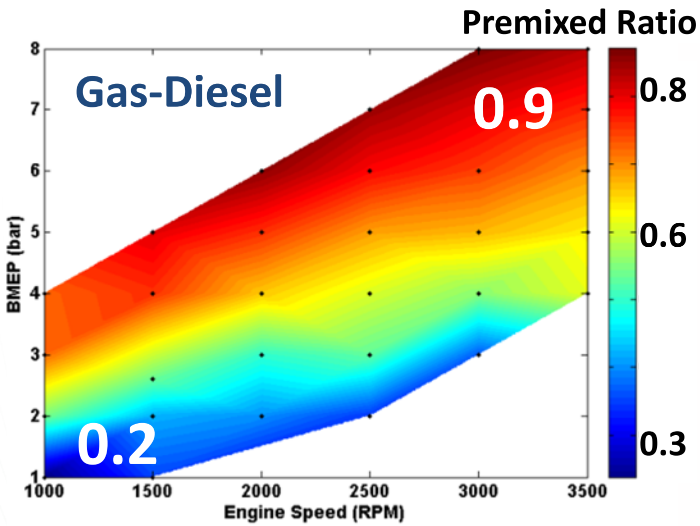


RCCI engine operating points at every 500 RPM and every 1.0 bar BMEP



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Q4 RCCI Fuel Economy Modeling Takeaways

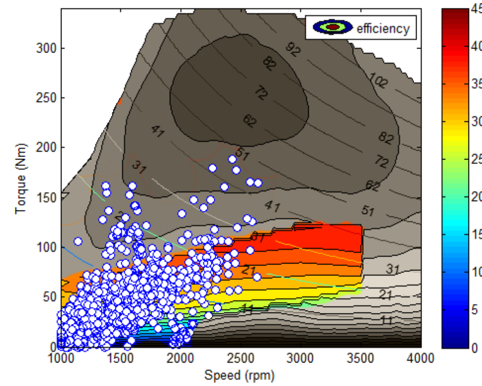
ACCOMPLISHMENTS (3/9)

RCCI has potential to offer greater than 25% fuel economy improvement a 2009 PFI baseline over all federal drive cycles as shown by vehicle simulations using experimental engine maps

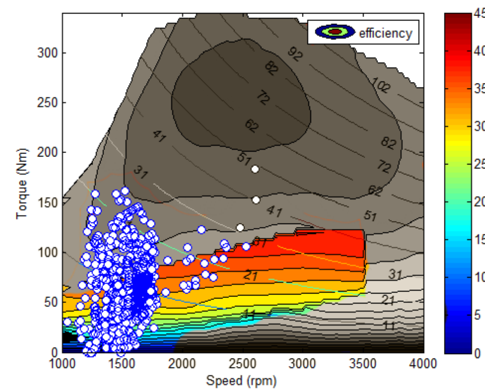
- **RCCI fuel economy improvements despite lack of complete drive cycle coverage (Further development possible)**
  - **UDDS = 62.7% drive cycle coverage by distance**
  - **HWFET = 62.8% drive cycle coverage by distance**
  - Hardware changes being considered (FY 15)
- **Results based on steady state engine data**
  - Does not currently address transient operation (FY 15)
- **Does not address aftertreatment effectiveness**
  - On going research at ORNL

	1.8L	2.4L	2.7L	4.0L
UDDS RCCI Improvement	30.1%	28.1%	42.6%	55.7%
HWFET RCCI improvement	36.1%	31.5%	40.0%	49.3%

UDDS – City Cycle



HWFET – Highway Cycle



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Current research and ACEC goals

- **Current RCCI results are showing promise on meeting 2020 ACEC stretch goal at 20% Peak Load @ 2000 RPM point**

2000 rpm, 4.0 bar BMEP Point from Premixed Piston

	CDC	RCCI UTG/ ULSD	RCCI E30/ ULSD	RCCI UTG/ B20
BTE (%)	33.4	35.8	35.7	$\boxed{36.1}$
NOx (ppm)	96	26	26	47
HC (ppm)	161	2164	3214	2864
CO (ppm)	322	1733	3329	1982
FSN (-)	1.02	0.01	0.01	0.01

Table 1. Engine Efficiency Baselines and Goals for Multi-cylinder Engines
(The stretch goals are intended to drive engine research. Goals are to be confirmed in CY 2012 by thermodynamic analysis.)

		2010 Baselines				2020 Stretch Goals		
Technology Pathway	Fuel	Peak Efficiency[1]	Efficiency[1] at 2 bar BMEP and 2,000 RPM	Efficiency[1] at 20% of the Peak Load at 2,000 RPM	Peak Load[2] at 2,000 RPM	Peak Efficiency[3]	Efficiency[3] at 2 bar BMEP and 2,000 RPM	Efficiency[3] at 20% of the Peak Load at 2,000 RPM
Hybrid Application	Gasoline	38	25	24	9.3	46	30	29
Naturally Aspirated	Gasoline	36	24	24	10.9	43	29	29
Downsized Boosted	Gasoline[4]	36	22	29	19.0	43	26	35
	Diesel	42	26	34	22.0	50	31	$\boxed{36}$

[1] Entries in percent Brake Thermal Efficiency (BTE).
[2] Entries in bars of Brake Mean Effective Pressure (BMEP).
[3] Entries in percent BTE that are equal to 1.2 times the corresponding baseline BTE.
[4] Downsized Boosted engine used premium grade fuel and direct injection.

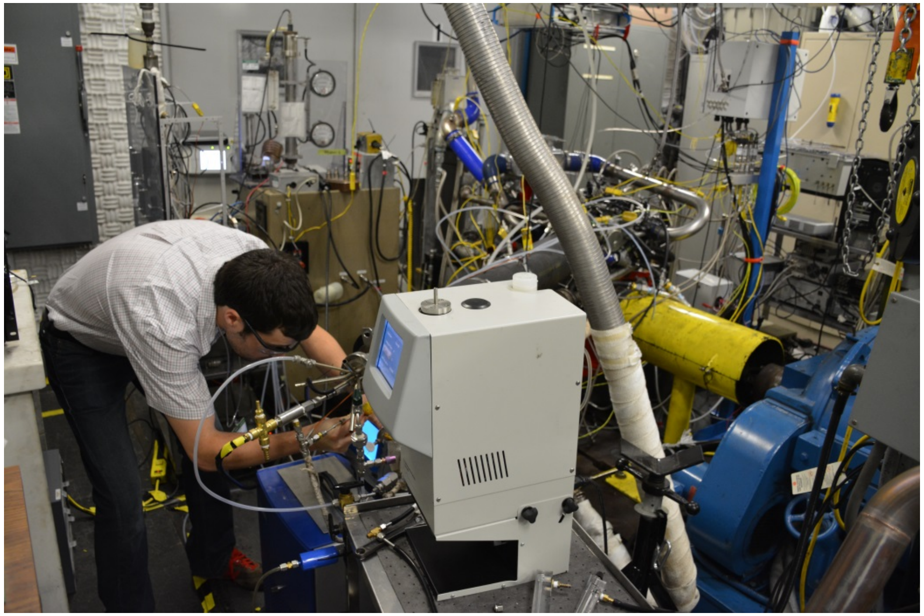
- **42.3% best peak BTE demonstrated @ 50% diesel peak efficiency load**
  - FY 15 investigating cooled LP-EGR and combustion system optimization

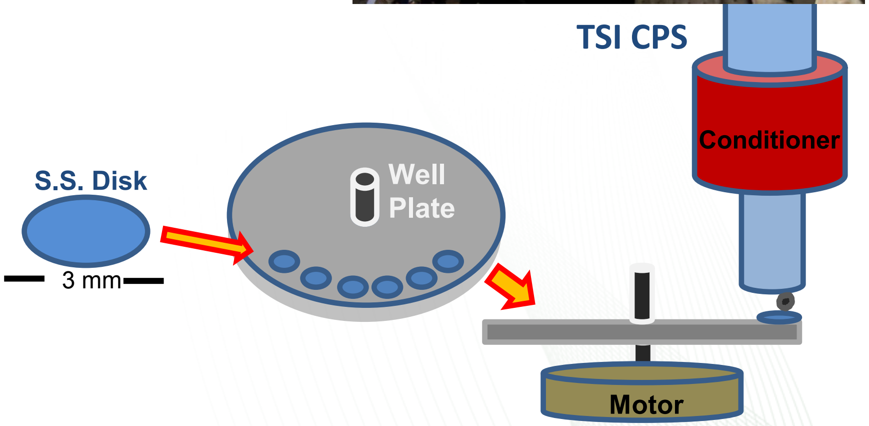
Table 1: http://www.uscar.org/commands/files_download.php?files_id=353

Collaboration with UMn Investigating Composition of RCCI PM Building off Previous ORNL RCCI PM Research

ACCOMPLISHMENTS (5/9)

- **Multiple RCCI points – stock piston (allowed CDC point baselines)**
  - 1500rpm, 2.6bar BMEP, 1500rpm, 4.0bar BMEP, 2600rpm, 5.8bar BMEP
- **Unique TSI prototype instrument – Condensation Particle Sampler**
  - Novel way to collect sufficient RCCI PM for GC-MS characterization
- **Catalytic stripper, TDMA, full particulate size distributions**
  - Results being summarized in joint paper
- **Large SMPS particle size distribution data sets taken for RCCI**
  - Analysis under way for statistical analysis compared to CDC

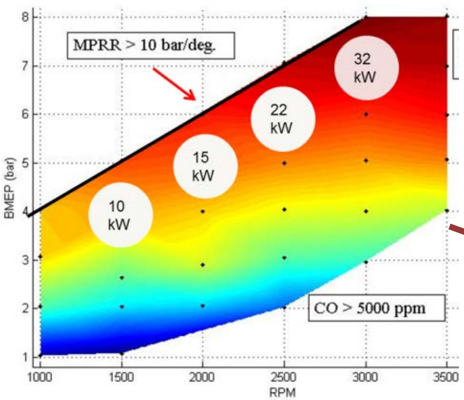




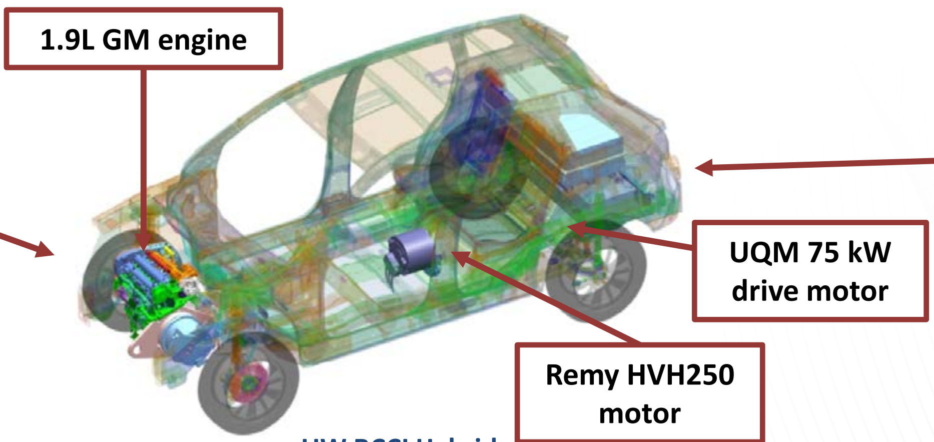
UW RCCI Evaluated at ORNL

- **Series hybrid RCCI vehicle**
  - Charge sustaining mode with various power/efficiency levels
  - Collaboration with National Instruments on Controller
  - Initial chassis dynamometer testing performed at FORD
  - Leverages UW DOE AVTC vehicle from EcoCAR
- **Further investigating multi-cylinder challenges**
  - Combustion stability / Controls for LTC on MCE/ load range limitations
- **Aftertreatment integration research including low-temp catalysts**
  - RCCI aftertreatment performance and feedback to CLEERS

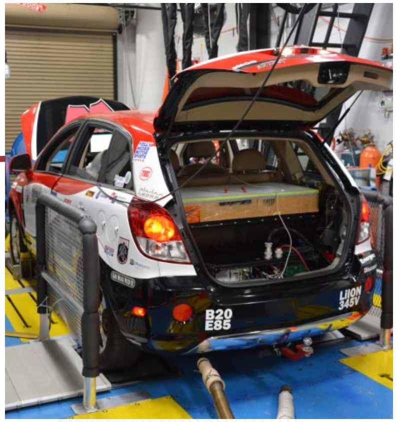
UW RCCI Hybrid in ORNL Chassis Laboratory



RCCI Power Levels for Series Mode



UW RCCI Hybrid



NI Powertrain Controller

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UW RCCI Hybrid being Evaluated at ORNL

- **Hot HWFET with charge sustaining RCCI operation**
  - 18 kW and 2,500 rpm point
- **Bagged emissions with aftertreatment-train in place**
  - Diesel oxidation catalyst /Diesel Particulate Filter combination
  - Three-way catalyst

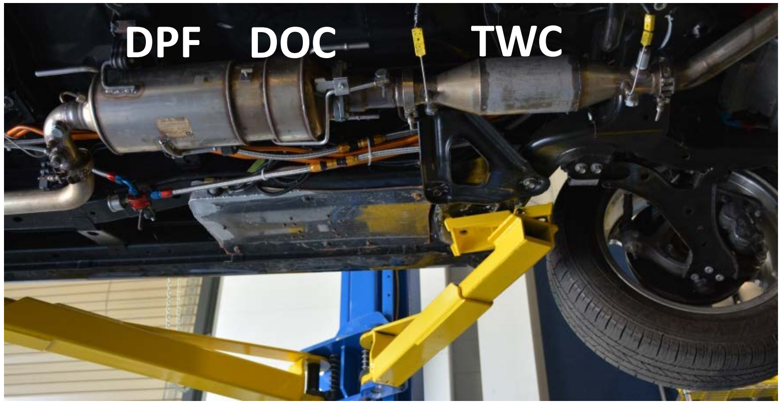
SAE INTERNATIONAL

Highway Fuel Economy Testing of an RCCI Series Hybrid Vehicle	2015-01-0837 Published 04/14/2015

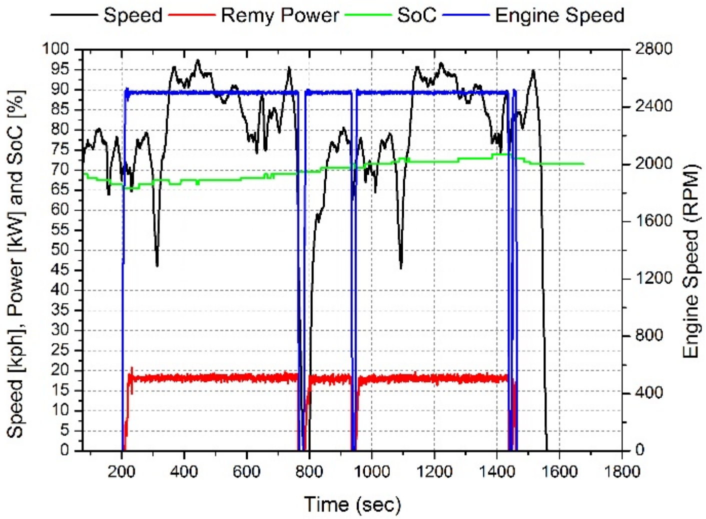
Reed Hanson, Shawn Spannbauer, Christopher Gross, and Rolf D. Reitz
University of Wisconsin

Scott Curran, John Storey, and Shean Huff
Oak Ridge National Laboratory

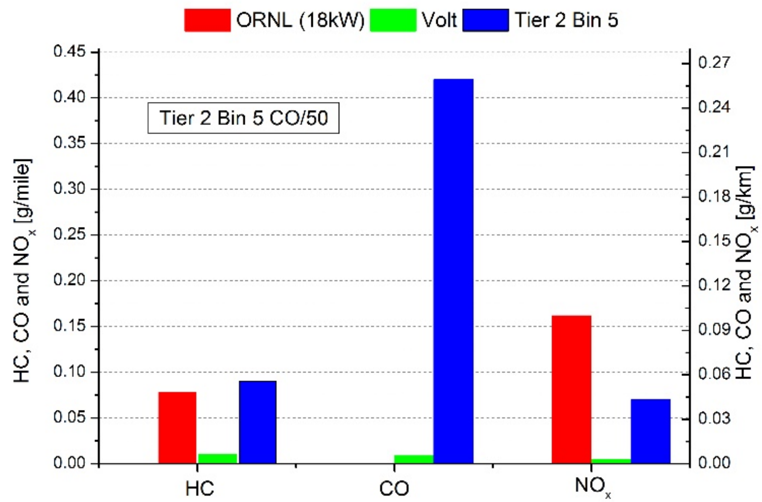
CITATION: Hanson, R., Spannbauer, S., Gross, C., Reitz, R. et al., "Highway Fuel Economy Testing of an RCCI Series Hybrid Vehicle," SAE Technical Paper 2015-01-0837, 2015, doi:10.4271/2015-01-0837.



Aftertreatment-Train Installed on UW RCCI Hybrid



Power during HWFET



Exhaust Emissions

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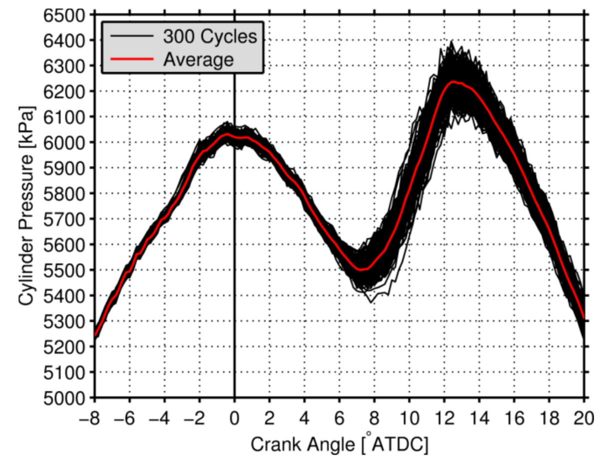
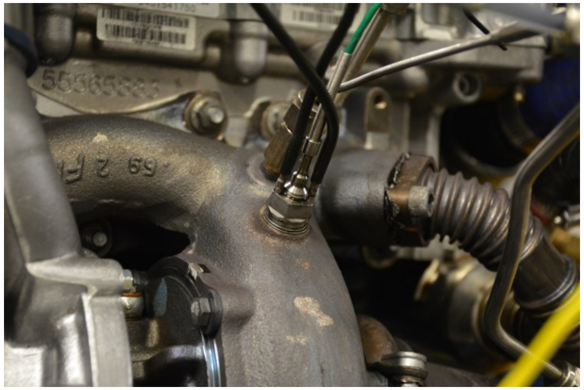
Upgraded in-cylinder pressure transducers + fast response piezo resistive intake/ exhaust pressure sensor

- **Machined GM 1.9 ZDTH head and installed flush mount pressure transducers with stock pistons**
  - Previous transducers used glow-plug adaptors
  - Caused ringing due to secondary chamber gas dynamics
    - Pipe oscillations with glow-plug adaptors
- **Accuracy for cylinder pressure based noise metrics + heat release analysis**
  - Added real-time ACEC calculated noise to NI control system
- **Water cooled piezo-resistive intake and exhaust**
  - Cycle resolved boundary conditions for improved model cycle simulation validation

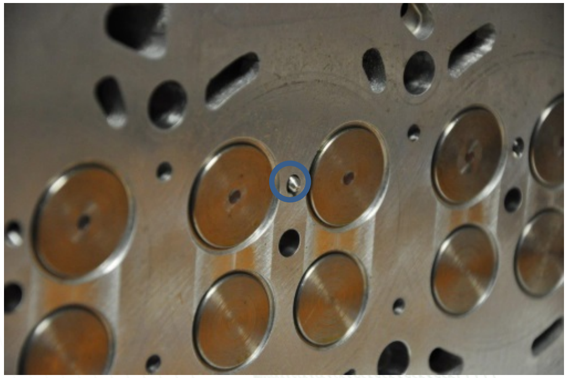


Non-filtered Cylinder Pressure Traces

Intake Sensor



Exhaust Sensor



Glowplug port in head

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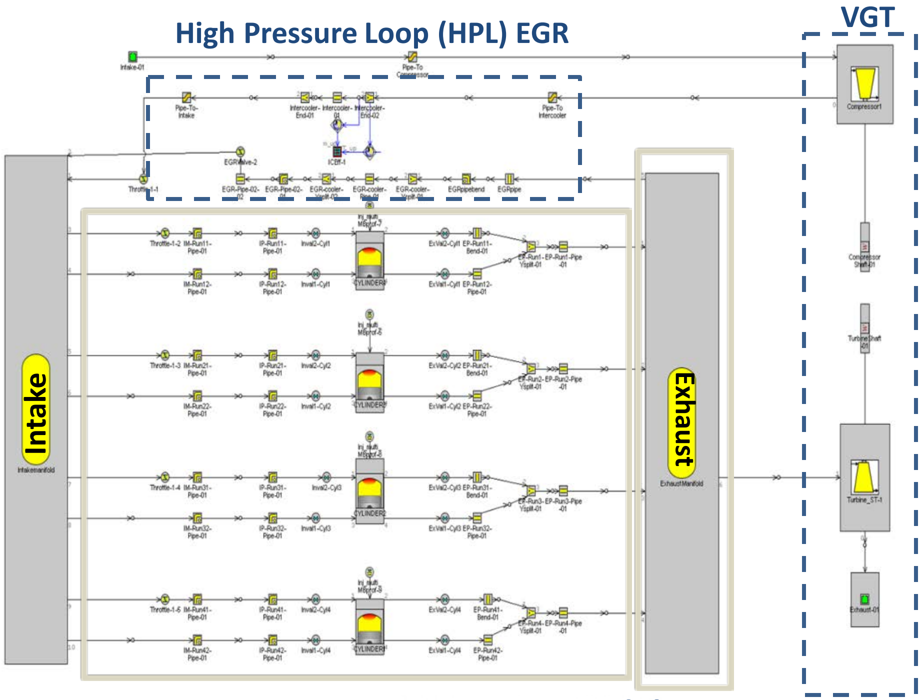
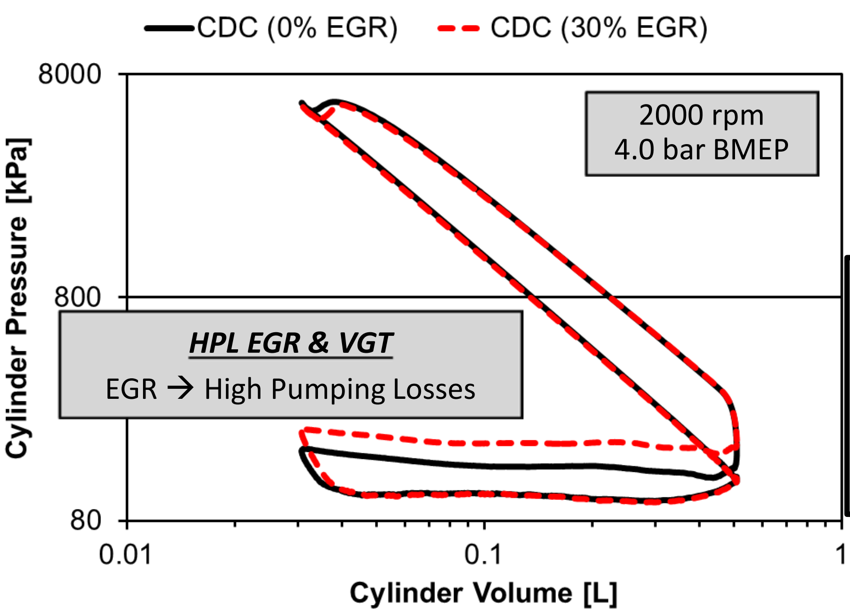
1-D cycle simulation of advanced combustion strategies focusing on air handling system efficiency (Clemson collaboration)

- Simultaneous high efficiency & low NOx/soot emissions requires high dilution (air + EGR)
- Using 1-D cycle simulation (GT-Power) to simulate a variety of advanced combustion strategies with stock system (high pressure loop EGR & VGT)
  - RCCI, Diesel LTC, GCI, CDC
- Evaluate the potential of alternative systems
  - Low pressure loop EGR
  - Series/compound turbocharging (BorgWarner R2S)
  - Supercharging



GM 1.9L Engine GT Power Model



CDC example shows best case

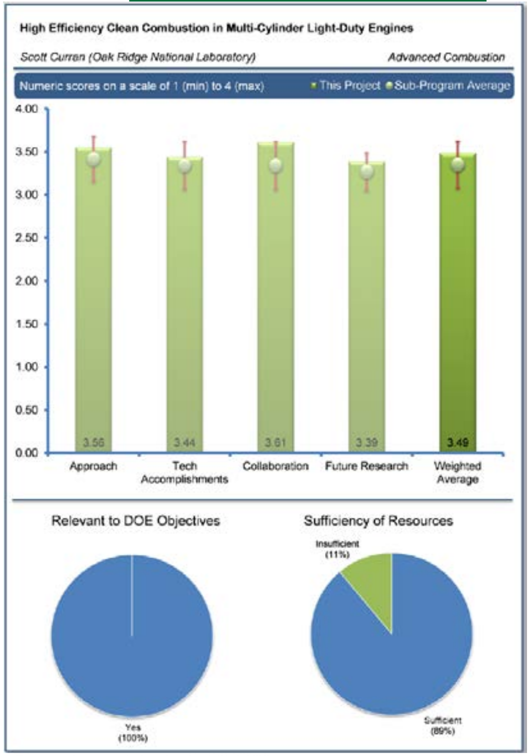
Lower exhaust enthalpy with LTC and competing needs from aftertreatment make this a significant challenge in MCE implementation

Reviewer Comments from FY 2014 – ACE016 - HECC

REVIEWER COMMENTS

Addressing significant Questions/ Recommendations

- **Reviewer mentioned this was a good approach, but should include the fuel economy impact of after-treatment in the vehicle simulation**
  - Currently working on updating aftertreatment models to be used in vehicle system simulations (backup slide)
- **The reviewer noted good progress towards vehicle-level estimates of emissions, but noted a need to consider cold start and catalyst light-off periods.**
  - The current multi-mode strategy would use CDC for cold start – the light-off periods for multi-mode transitions has been investigated in a recent paper by Prikhodko et al.
- **Critical to incorporate appropriate systems-level controls (model-based controllers would be ideal) to control RCCI through transient operation**
  - This an excellent point and similar feedback has focused the long term strategy of this project to hopefully addresses this and investigate both the challenges and opportunities with transients and multi-mode switching



Positive Comments

- **Reviewers noted "the approach was excellent in that it seeks to be as relevant to real-world application as possible, using multi-cylinder engines, calibrating it over the test cycle"**
- **The reviewers "felt that it was very useful to see RCCI tested in real conditions" and that a "a system-level approach was needed for evaluating vehicle-level emissions and efficiency benefits"**
- **Reviewers noted the" work was very relevant to the research on future systems" and that HECC was an important high-risk, high-reward technology for LDVs, and that this project was addressing all the appropriate area .**

Comments cited above were paraphrased as appropriate from 2012 Annual Merit Review document, http://www1.eere.energy.gov/vehiclesandfuels/pdfs/merit_review_2012/2012_amr_04.pdf

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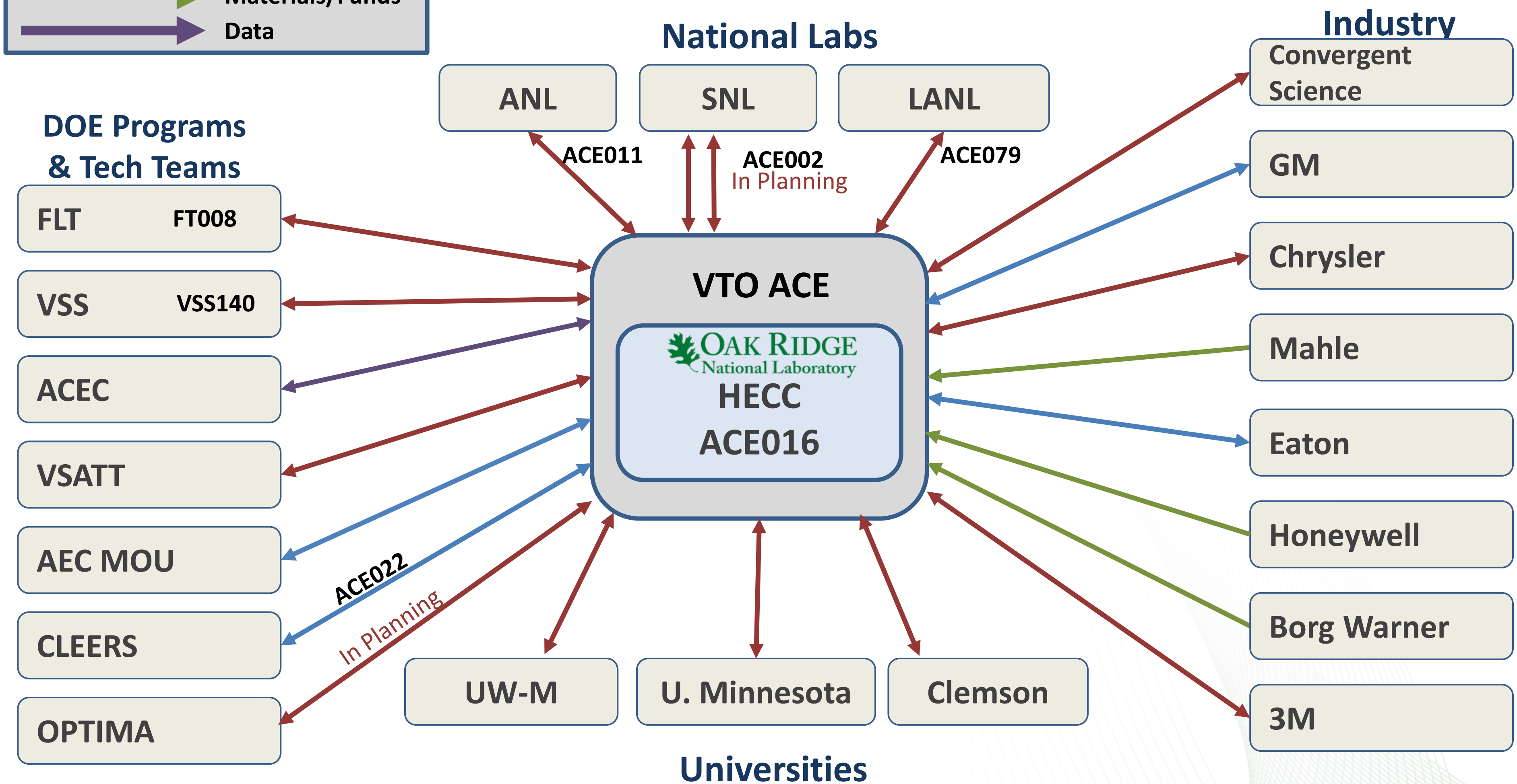
ACE projects leverage resources and expertise across industry, universities and DOE programs to meet these objectives

Key: Type of Partnership
- Information
- Collaboration
- Materials/Funds
- Data

HECC Project Main Objective: To develop and assess the potential of advanced combustion concepts, such as RCCI, on multi-cylinder engines for improved efficiency and emissions along with advanced emission control technologies

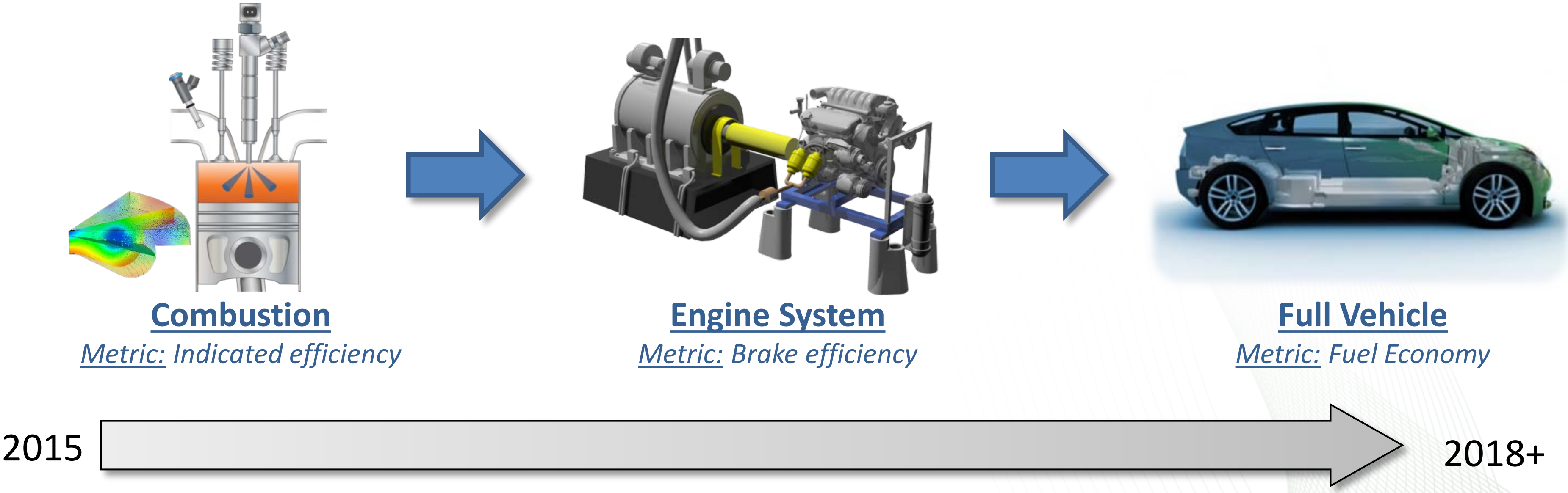


More details in backup slide

Remaining Challenges and Barriers

Remaining challenges and barriers being addressed in three year plan

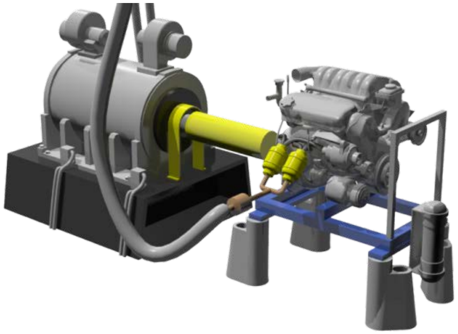
- **Load expansion:** enabling LTC load expansion through hardware optimization
- **Transients:** transient LTC operation and multi-mode transients (w/ aftertreatment effects)
- **Controls :** real-time and next cycle feedback controls for enabling HECC
- **Aftertreatments :** after-treatment challenges with regards to CO and HC emissions, as well as low exhaust temperature
- **Air-handling:** matching air handling to LTC and multi-mode strategies



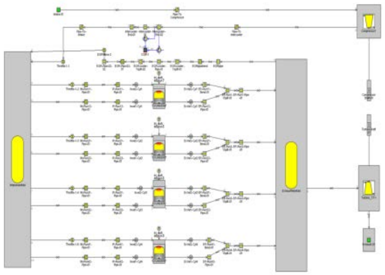
Future Work

FY 15

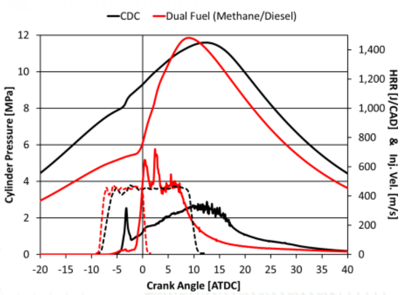
- **Q3 and Q4 DOE Milestones – RCCI/ multi-mode with stock pistons**
  - Specific efforts will be on investigation detailed multi-mode transitions
    - Improved model development – understanding challenges and potential opportunities
    - Collaboration with ANL on guidance to be used for LTC mapping
    - Integration of ACEC noise guidelines and ACEC efficiency guidelines
- **Further investigating multi-cylinder challenges of advanced combustion**
  - Enabling technologies including advanced air-handling/ pistons/ sensors
  - Combustion stability / controls for LTC on MCE
  - Aftertreatment integration experiments
- **Couple MCE experiments to high fidelity CFD modeling for insights into efficiency/emissions**
- **Transient hardware-in-the-loop for advanced combustion research**
  - Will provide additional capabilities to address aftertrement and drive cycle challenges
- **Aftertreatment integration research including low-temp catalysts**
  - RCCI aftertreatment performance mapping and feedback to CLEERS
- **Collaboration with SNL on injector studies for combustion noise reduction**
  - ACE002 – Steve Busch



Aftertreatment Integration



Cycle Simulations



CFD to Accelerate LTC R&D

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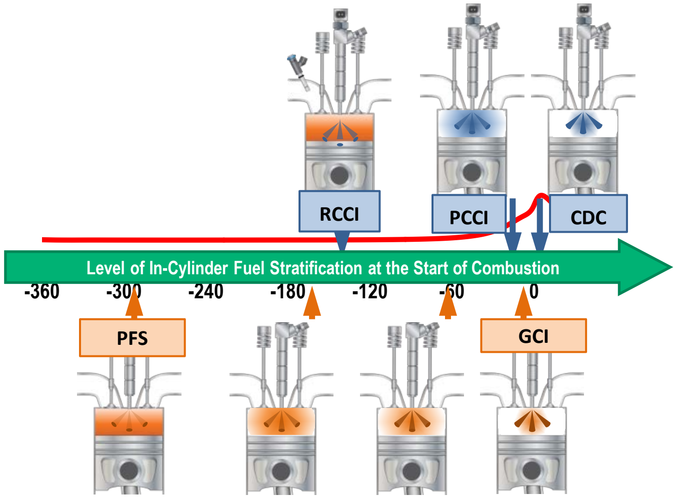
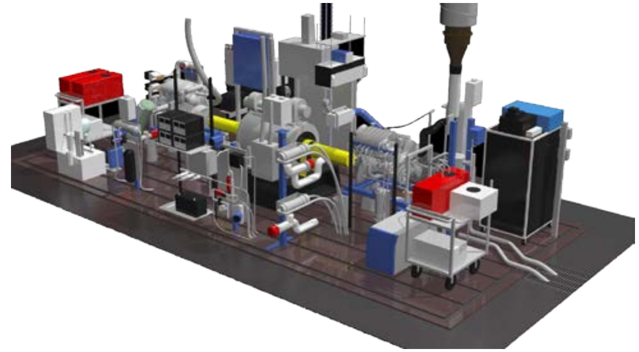
Future Work focusing on multi-cylinder implementation challenges of advanced combustion modes including multi-mode combustion

FUTURE WORK (2/2)

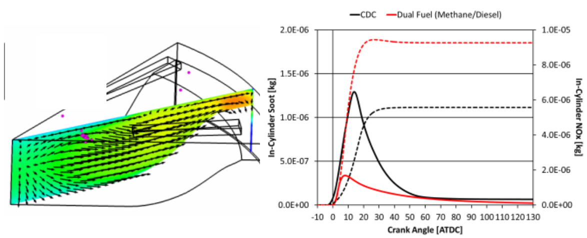


Dual- and Single-Fuel Multi-Mode Advanced Combustion

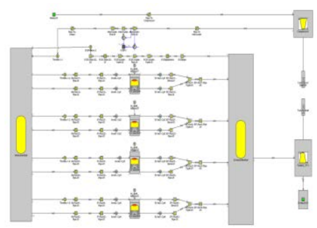


Engine + Aftertreatment Experiments

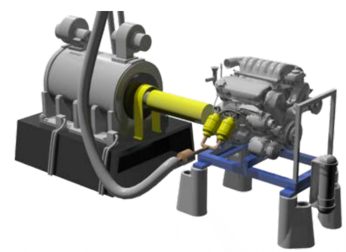
Vehicle System Integration



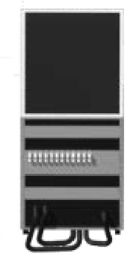
CFD for Accelerating High Efficiency Combustion Development and Analysis



Cycle Simulations for Air Handling Development and Analysis



Detailed HC& PM Characterization



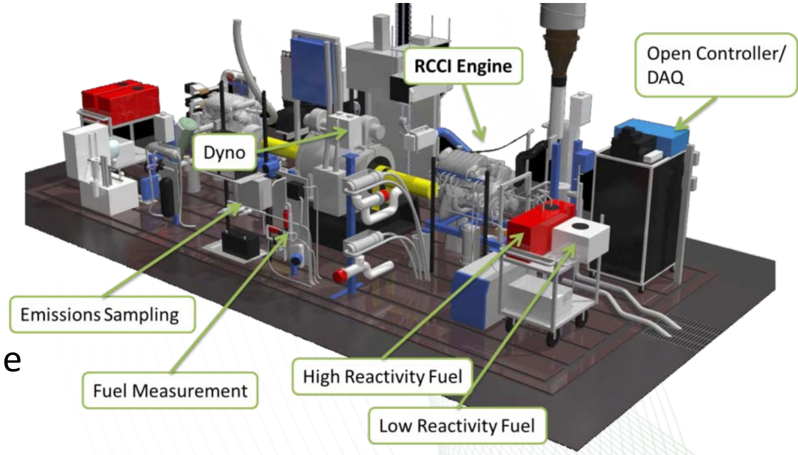
HIL & Transients

- RCCI Mapping
- HIL & Transients
- CFD & Cycle Simulations Accelerating Maps
- HIL Drive Cycle Experiments
- Full Vehicle Integration Experiments

2015 — 2016 — 2017 — 2018

Summary

- **Advanced combustion techniques such as RCCI shown to increase engine efficiency and lower NOx and PM emissions demonstrating potential for increased fuel economy**
- **Comprehensive engine systems approach to advanced combustion research**
  - Multi-cylinder advanced combustion experiments
  - Aftertreatment integration
  - Vehicle systems level modeling
- **Current research focused on investigating fuel economy potential of LTC**
  - RCCI combustion research and development leading to engine mapping
  - Aftertreatment studies to understand interdependency of emissions control and system efficiency
  - Related research into loss mechanisms, combustions noise and controls
- **Interactive feedback and collaboration**
  - Industry and Tech Teams
  - University and National lab partners
- **Future work includes progressive milestones**
  - Transient operation for advanced combustion/ multi-mode
  - Low temperature catalysts



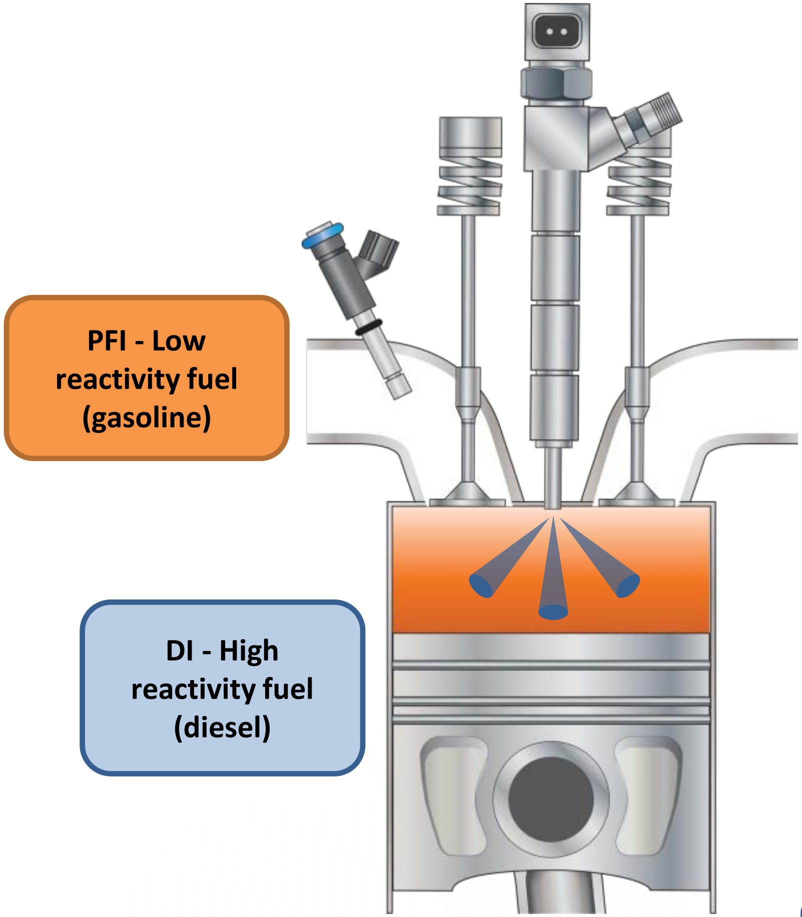
Backup Slides

Contact
Scott Curran
curransj@ornl.gov, 865-946-1522

Background: Dual-fuel Reactivity Controlled Compression Ignition (RCCI)

Back-Up 1

- **Reactivity controlled compression ignition (RCCI) allows precise reaction and heat-release control**
  - A low-reactivity fuel is introduced early and premixed with air.
  - A high-reactivity fuel is injected into the premixed charge before ignition.
- **RCCI increases engine operating range for premixed combustion**
  - Global fuel reactivity (phasing)
  - Fuel reactivity gradients (pressure rise)
  - Equivalence ratio and temperature stratification
- **RCCI offers both benefits and challenges to implementation of LTC**
  - Diesel-like efficiency or better
  - Low NOx and soot
  - Controls and emissions challenges



Low = Prevents Auto-Ignition **Fuel Reactivity** **High** = Promotes Auto-Ignition

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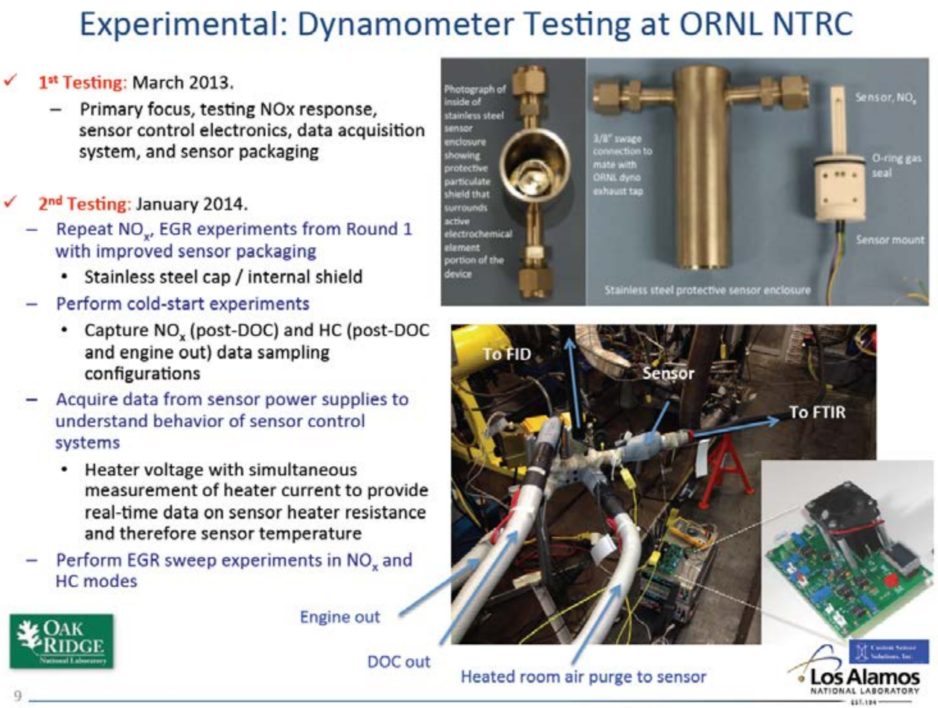
LANL Collaboration (ACE079)

Back-Up 2

- **Scientists from Los Alamos National Laboratory visited ORNL to study the performance of their novel engine exhaust sensor technology on ORNL's lean-burn gasoline direct injection engine.**
- **The study was conducted under the National Transportation Research Center User Facility program at ORNL. Multiple mixed potential sensors for measuring ammonia, oxides of nitrogen (NOx), and hydrocarbons were simultaneously evaluated in the engine exhaust for understanding the response of the sensors to different engine operating conditions.**
- **The NOx and hydrocarbon sensors could quantitatively track concentrations in the engine exhaust, and the ammonia sensor showed excellent sensitivity over concentrations ranging from 10-100 ppm.**
- **A prototype ammonia sensor was also evaluated on an automated flow reactor to collect calibration curves and quantify sensor cross-sensitivities.**
- **All three of the sensors show promise for various exhaust emissions sensing applications**



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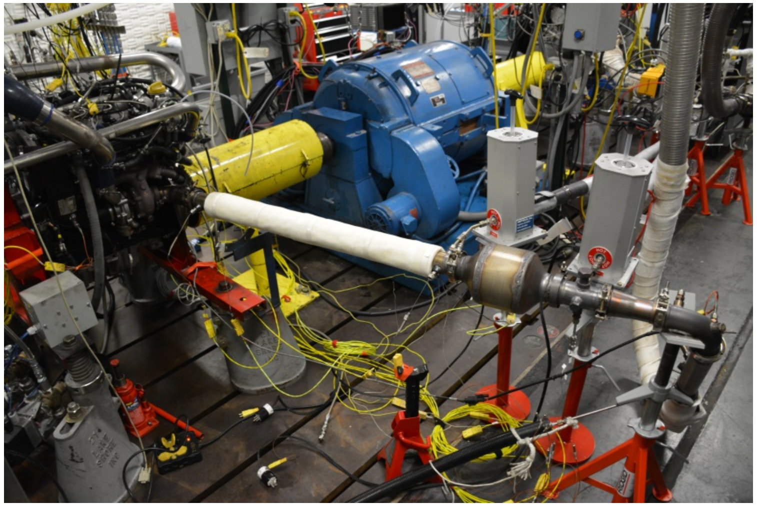
3M Collaboration

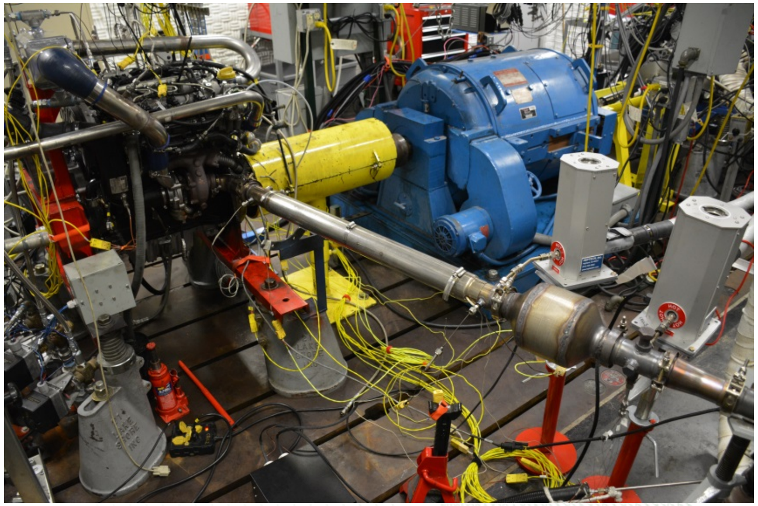
Back-Up 3

- In this study, 3M's advanced insulating material (1250NC) was studied on the ORNL RCCI engine.
- A DOC installed downstream of the two-feet long insulated exhaust pipe to look at its oxidation activity during the multi-mode engine operation.
- The performance of the 1250NC insulating material was compared to double and single-wall exhaust pipes. Exhaust monitored with FTIR and CAI analyzers before and after the DOC.
  - The experiments are designed to access the implications of thermal management on the DOC performance during multi-mode engine operation, such as DOC oxidation activity as a function of temperature and the extent to which the insulating materials can keep the catalyst above the light-off temperature and prolong the RCCI operation.
- The "light-off" temperature sweep was performed by operating the engine in conventional combustion mode with higher exhaust temperature and then switching to RCCI combustion with lower exhaust temperature.
  - As the exhaust cools down to a set point, engine will be switched back to conventional combustion and the cycle will be repeated.

Novel 3M Exhaust Insulation Material



Double Wall Insulation Experiments

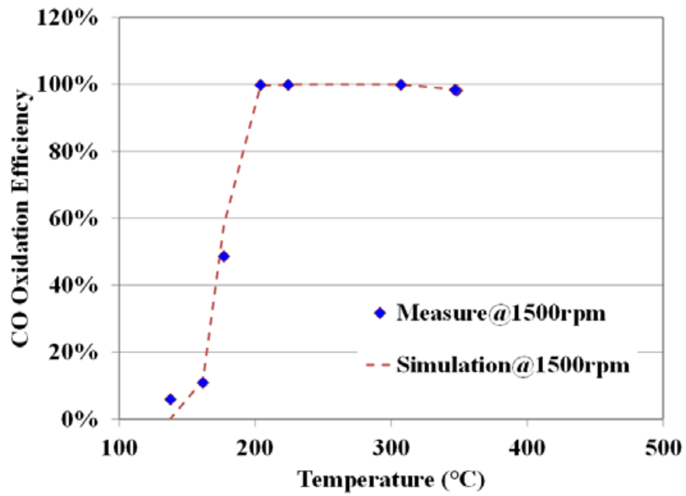


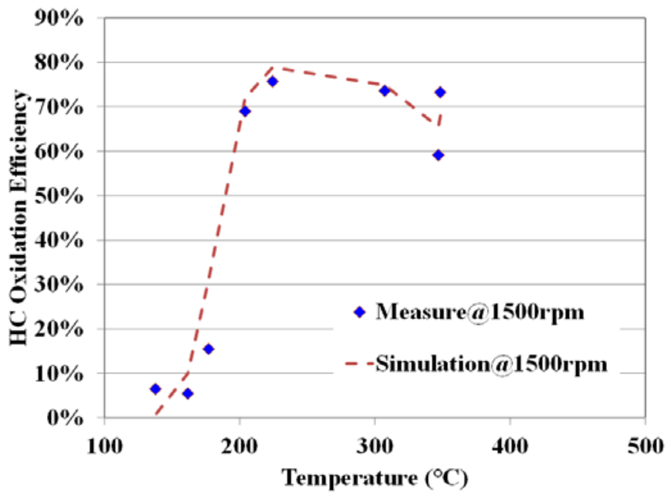
Update DOC catalyst models for multi-mode RCCI combustion

Back-Up 4

- **Fitted reaction rates of CO/HC/NO oxidation as a function of the DOC operating temperature [2]**
  - The reaction rates were optimized using Matlab optimization functions for each DOC performance at 1500rpm and 3000rpm engine series operations
  - The slope and intercept can be used as active energy and pre-exponential factor
- **Critical to update moving forward simulating aftertreatment effectiveness with RCCI multimode (CDC complete – currently working on RCCI data)**
  - Simultaneously high HC and CO with lower temperatures effects with RCCI not well understood for DOCs (competing)
  - Not only the amount of HC and issue but the composition of RCCI HC for DOCs developed for CDC HC, CO and Temps
  - DOC light-off criteria being incorporated into next multi-mode control strategy (critical for Tier III standards HC+NOx)

Comparison of the simulated and measured CHC oxidation





** In collaboration with VSST support task*
VSS 140 Impacts of Advanced Combustion Engines

[2] In coordination with CLEERS Activity
ACE022 CLEERS Analysis and Coordination

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Collaborations and Industry Feedback

Back-Up 5

- **University Partners**
  - The University of Wisconsin-Madison – RCCI modeling and RCCI Hybrid
  - The University of Minnesota – RCCI PM Collaboration
  - Clemson University – Cycle Simulations for Advanced Combustion Air-handling
- **Industry Partners**
  - ACEC/ USDRIVE – Goal Setting, Noise and Drive Cycle Estimates
  - GM - GM 1.9 – Hardware and LTC noise discussion
  - Cummins – Hardware and ECU support of HD RCCI project
  - Chrysler – Engine Data for Q4 milestone
  - Convergent Science – Providing RCCI data – receiving licenses for CFD collaboration
  - 3M – Collaboration on heat transfer experiments for aftertreatments
  - MAHLE – Premixed Compression Ignition Piston Design
  - National Instruments – Hardware for RCCI Hybrid Vehicle
  - FORD– Sharing RCCI data and RCCI discussions
  - MECA – Catalysts supply and industry feedback
  - Borg Warner – Hardware and discussion of advanced air handling
  - Energy Company– Fuel effects collaboration for LTC
  - SAE – Chair of Dual Fuel Supersession -> interacting with other RCCI researchers
- **VTO Activities**
  - VSST – ACE support task (VSST 140)
  - FLT – Advanced fuels for advanced combustion engines
- **DOE AEC/ HCCI working Group**
  - Research is shared with DOE's AEC/HCCI working group meeting twice a year
- **Other DOE Labs**
  - LANL – Provide MCE LTC engine for evaluation of mixed-potential sensors
  - PNNL – SPLAT RCCI PM campaign
  - SNL – Discussions on LTC, Injector Noise

Model Development and Refinement

Hardware for LTC

Feedback and Data Sharing

Goal Setting

Leveraging and Outreach

Oak Ridge National Laboratory